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PROSPECTS FOR SUPERCONDUCTING ACCELERATORS

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The rapid recent development of technology in the use of superconducting materials has raised the question as to whether a new generation of accelerators based on these techniques can now be designed and built, and, if so, whether they will have significant advantages or lower cost than machines based on present principles and techniques. In particular, it has been suggested that superconducting magnets might be substituted for the iron-cored magnets with copper conductors of conventional accelerators, at lower unit cost (cost per GeV of beam energy). The purpose of this study is to assess the present status of technical developments to see whether this suggestion is valid for accelerators in the multihundred GeV energy range, and, specifically, its significance relative to the NAL 200-GeV machine now under construction.

The incentive for the use of superconducting magnets is to reduce the very large power requirements of conventional magnets, which involves large and costly power equipment and also high operating charges. Another purpose is to reduce orbit radius for a given particle energy by use of very high fields (40, 60 or even 80 kG), thus reducing the size and cost of the accelerator housing and of other associated facilities.

One feature is clear: the technology of cryogenics has made significant advances during the past five to ten years. Commercial firms have produced a variety of superconducting materials and have measured their properties. Empirical understanding of the performance of such materials is well advanced. Workers in the field have built and operated several kinds of prototype magnets with superconducting materials, producing solenoidal, dipole and quadrupole magnetic fields, have identified many of the practical limitations, and have conceived solutions to some of the problems. A few large magnets for bubble chambers have been built successfully, and still larger ones are under construction. In most of these applications the coils are of solenoidal or Helmholtz shape and the magnetic forces are retained by large circular ring structures. Only a few have used iron flux-return circuits. More pertinent developments are for dipole bending magnets with transverse fields across long, tubular cores, and for quadrupoles with similar beam-sized apertures, developed primarily for use in the handling and focusing of emergent particle beams. To date five or six such bending magnets or quadrupoles without iron cores have been put into service for experiments. So far they have performed to expectations.

A few enthusiasts have extrapolated on their successes and have proposed conceptual plans for accelerators utilizing superconducting magnetic fields for bending and focusing the beams. Some have made tentative cost estimate comparisons for such hypothetical accelerators which favor the superconducting machines. However, few of these estimates have been based on a choice of energy and other parameters which make them directly comparable with the NAL 200-GeV design estimates.

Technical Feasibility

The pertinent questions are of two types: those applying to the technical feasibility of cryogenic systems and techniques as applied to accelerators, and those pertaining to relative costs. Progress in the cryogenic field was summarized at the Brookhaven Superconductivity Summer Study[1] in 1968. These Brookhaven proceedings are not yet published, but many of the significant individual papers have been distributed and discussed. Some of the more optimistic conclusions were summarized and reported in an article in Scientific Research.[2]

The most pertinent question as to feasibility involves the eddy current and ac losses in superconducting windings associated with the pulsed operation of an AG synchrotron. With presently available shapes and sizes of conductors, all designers agree that these losses are excessive, resulting in refrigeration cooling requirements of many kilowatts of power at 4°K. The present cost of refrigeration at 4°K (at the 500-watt unit level) is about \$400 per watt. For a 300-GeV accelerator the cost of refrigeration could be as much as \$100 million,[3] greatly in excess of any savings in magnet power. Furthermore, the cost of the pulsed power supply to produce the required magnet cycle in a superconducting accelerator is not significantly less than for conventional magnets.

At the Brookhaven Summer Study several papers dealt with the effect of the shape of the conductor, specifically the use of conductors of very small cross section. The most significant analysis was presented by Peter Smith of the Rutherford Laboratory, who re-emphasized the importance of extremely small conductor cross-sections. He showed that a twisted cable formed of superconducting filaments of 1-mil diameter, each embedded in a copper sheath, would average out the induced fields in the conductors due to pulsing and reduce power losses. (This is similar to the use of "Litz" wire in the early days of radiofrequency to reduce resistive power losses.) Hopefully, the thermal losses due to pulsing can be significantly reduced by conductors embodying this principle. Several laboratories are now developing experimental model magnets with such filamentary conductors. But no body of experience exists, and the commercial availability and cost of material has not been established.

Many other technical problems in the construction of dipole magnets with superconducting coils are still unresolved or in the initial stages of development. In order to achieve uniform fields, the coils are wound around a cylindrical core in crescent or lunar cross section. Techniques for winding and shaping such coils are still at the laboratory stage; much engineering development remains to give the quality of reproducibility from magnet-to-magnet required for an accelerator system, which is of the magnitude of $\pm$ 0.01%. The reproducibility of magnetic field from cycle-to-cycle in pulsed operation is essentially unknown, but must be kept within approximately the same limits. Another requirement is field uniformity within the beam aperture, which must also be kept within tight limits. Presumably, this can be accomplished with a sufficient number of precisely located conductors. Some measurements of field uniformity have been made on individual laboratory magnet models, but not yet to the required precision.

To attain adequate uniformity and reproducibility, one of the essential engineering developments is the support system to restrain the large magnetic forces. The force supports may have to be located within the dewar, which requires large dimensions and results in high thermal losses. Or, they may have to penetrate the dewar, which involves high thermal-conduction losses. Some designers envisage an outer iron magnetic flux-return circuit enclosing the low-temperature dewar and the windings for magnetic shielding. It should be possible to utilize this iron frame for anchoring the force supports for the coils. Due to its large size this iron jacket is in fact larger than the normal iron circuit in a conventional magnet. Such an iron shield involves an additional cost which is often not included in estimates by designers of superconducting magnets.

Other reports were based on new techniques of a more speculative character, with potential applications to accelerators. H. A. Schwettman and others from Stanford reported success with a short model of a superconducting cavity for a microwave linear accelerator, and their designs for a 500-ft linac. And they speculated on a temperature-distribution control system based on the use of superfluid helium (2.2°K) rather than ordinary liquid helium, which might take advantage of the anomalously low viscosity and high thermal conductivity of the superfluid state. This could lead to very small temperature differences, lower distribution losses and lower liquid-helium pumping requirements.

One general conclusion on the status of superconducting technology is that essentially no experience exists on applications to systems. Individual magnets and devices have been operated successfully but not a string of magnets all performing simultaneously. Accelerator experience shows that many of the major problems requiring development arise when many individual components are assembled and operated as systems. In the cryogenic field a variety of new engineering construction and control techniques must be developed to provide the stability and reproducibility required in the simultaneous use of many units. Engineering experience and cost analyses are also required to determine the best method of cooling a large array of sub-units to low temperatures. Such experience with systems now seems essential in the superconducting field.

On the other hand, present prices for materials and refrigeration equipment are high in this recently developing technological field. Estimates have been made of the probable decrease in cost in the future of superconducting materials and refrigeration equipment. Some speculative designers have used such estimates to illustrate their hope that costs may become much lower in the future.

Proposals for Superconducting Accelerators:

a. Separated-function AG synchrotron:

Several papers were presented at the Brookhaven study by M. A. Green[4, 5] of the Lawrence Radiation Laboratory pertaining to superconducting accelerators in the energy ranges of 100 GeV and 1000 GeV. The papers present cost analyses based on variation of some critical machine parameters. For the 100-GeV machine the effect of time cycle on the ac and eddy current losses was considered.[4] The superconducting material was presumed to be Nb-Ti, in the form of a twisted cable of 0.001 inch filaments, in order to compute the losses. The cost estimates were prepared using a set of parametric cost equations, programmed for computer analysis. An estimate of machine component costs was obtained which showed that the short-cycle (2 sec) machine cost was greater than for the long-cycle (20-sec). Costs were also estimated for a 1000-GeV synchrotron. An LRL Engineering Report[5] by Green presents parametric cost equations used and gives further details based on varying other parameters. Although direct cost comparisons with the NAL 200-GeV design estimates are not available, a qualitative analysis by Green and L. C. Teng of NAL (private communication) shows that the estimates for superconducting magnets plus power supplies and refrigeration, for a 200-GeV size, exceed the NAL estimates for the equivalent items of magnets plus power supply. Although Green's estimates are the most realistic ones available at present, they presume that a continuing program of development will be required to achieve the goals.

Other contributors to the Conference proposed accelerators for other energy goals. Kruger and Snyder[3] presented calculations on several systems including FFAG (fixed field) accelerators. For comparison, they described a superconducting version of a large-orbit AG synchrotron for 300-GeV energy. Their cost estimate for "some critical items" was $150 million, of which $100 million was for the cost of refrigerators at present prices. The low estimates for some other items listed illustrates the problem of evaluating such partial cost estimates to obtain any realistic comparisons.

W. Sampson of Brookhaven suggested that greater relative savings could be made in the 2000-GeV range by using superconducting magnets. He proposed use of a peak bending field of 60 kilogauss for which the magnet circle radius would be only 50% larger than the NAL 400-GeV orbit. He estimated the magnet-refrigerator-dewar system at about $100 million, and claimed the magnet system would be three to five times lower in cost than a conventional magnet system scaled-up from the NAL. No estimates were made of the cost of components and facilities, or of total costs.

b. Fixed-field synchrotrons:

The major thrust in the report by Kruger and Snyder[3] was on the utilization of superconducting magnets for FFAG accelerators based on the MURA designs of some years ago. Kruger described an FFAG model currently under discussion at Brookhaven, of a separated-function, spiral-ridge synchrotron capable of producing 1.2-GeV protons with a peak magnetic field of 50 kilogauss. He extrapolated from this model design to a 300-GeV FFAG accelerator with an overall radius of 400 meters. For both, he proposed to use Nb_3-Sn ribbon superconducting material of 1/2 inch width. In his cost estimates he used present prices of this conductor, but also speculated on a future price lower by a factor of 20. In his cost comparison of "some critical items" he presents a result highly favorable to the FFAG. It is difficult to comment objectively on such a non-objective comparison. At best, this report must be labeled speculative and incomplete.

Another concept intended to solve the problem of heat losses in pulsed superconducting accelerators has been presented by M. L. Good[6] of Stony Brook University. He suggests a technique by which pulsing can be eliminated and the superconducting magnets operated in the dc mode. The scheme is to rotate portions of the bending and quadrupole magnets in the orbit of a synchrotron, around the beam axis. Roughly, if each magnet is conceived as being in four parts, two could be fixed and two could be rotated slowly about the axis in opposite directions. The resulting net radial forces on the circulating particles would be equivalent to those from average fields varying from zero to maximum and back to zero in each cycle. Good analyzes the effects of such varying forces on the particle orbits and concludes that both bending and focusing motions in the orbit are stable. No comments were made on the engineering problems involved in rotating superconducting magnets, or on any cost comparisons.

Storage Rings:

The most likely prospect for success of cryogenic technology in the accelerator field is for storage rings to provide colliding beam interactions, since storage rings use steady dc magnetic fields and are not subject to the additional problems associated with pulsed accelerators.

This prospect has recently been explored at the NAL in a Storage Ring Design Report, 1968.[7] The energy chosen was 100 GeV in each of two intersecting rings. The study drew upon the part-time efforts of 16 NAL staff members and utilized the advice and help of 20 or more scientists from other institutions with experience in storage ring planning. Cost estimates were based on unit costs for accelerator components used in the NAL 200-GeV Design Report, and on the services of W. M. Brobeck and Associates for conventional buildings and facilities. As a result, the cost estimates are closely tied to the 200-GeV estimates.

A conclusion which is implicit in the design chosen for the storage ring, is that the available sources of information on the engineering features and costs of high-field superconducting magnets are insufficient to provide an adequate engineering estimate of costs at this time. As a result, the NAL storage ring design uses iron magnets to provide field-shaping, and is excited to 20 kilogauss fields in the bending magnets and to a gradient of 250 kG/m in the quadrupole magnets. This decision is not a denial of the possible use of high-field superconducting magnets in a later design before the machine is built, but is taken in order to obtain a responsible estimate of cost for planning purposes. Choice of a bending field of 20 kG and the desired particle energy of 100 BeV, plus the estimated length of six straight inserts in the orbit, leads to an orbit radius of 1/3 that of the main ring, or 333 meters.

In the NAL storage ring study the primary effort went to the design of conventional iron magnets with water-cooled copper coils, for which the power requirements are about 20 megawatts. In addition, however, two types of cryogenic coils are conceived, one using superconductors in a thermally insulated dewar within the coil window and liquid He cooling at 4° K, and one using high-purity aluminum at 20° K to reduce ohmic losses. The reduced size of conductors (including thermal insulation) results in smaller coil windows and smaller iron magnets for the same useful field region. The total refrigeration capacity at 4° K for the superconducting coil, including estimated heat losses through spacers and supports, is estimated to be 7.3 kilowatts. For the aluminum coil at 20° K the dominant heat loss is ohmic and the total refrigerator power is estimated to be 175 kilowatts.

The three types of coil are used in the cost estimating, including the different amounts of installed magnet power and of refrigeration. The estimated total costs for the 100-GeV storage ring facility, using the three types of coils, are given below (costs in millions of dollars):

	Conventional: (Cu)	Superconducting: (Nb-Ti)	Cryogenic: (A1)
Technical components	44.	40.	56.
Conventional facilities	36.	34.	35.
Total estimated cost	80.	74.	91.

Costs for the superconducting and cryogenic coil types do not include costs of development or the time required for development. No full-scale prototypes of iron-cored magnets have yet been built using superconducting windings; only one laboratory (Brookhaven) has built a model with cryogenic aluminum coils.

Furthermore, costs of cryogenic and superconducting materials may change in the future. It seems clear that at the present time the differences in the above totals are not significant. The only valid conclusion is that no major cost savings are apparent.

In an appendix to the NAL Storage Ring Design Report, the use of high-field superconducting magnets to replace the 20-kG magnets is briefly studied. Two field ranges are considered, 40 kG and 60 kG, with the bending magnet radii reduced proportionately to achieve the same 100-GeV energy. In each case the uniform field region within the superconducting windings is circular in section with a diameter equal to the radial width required at 20 kG. The helium container is thermally insulated and surrounded by a thick iron magnetic flux-return shield. The primary purpose of the iron is to shield one storage ring from the stray flux of the other. Current density in the superconductor (Nb-Ti) is chosen to provide "stable" operation; at the present time it is considered imprudent to commit to a higher current density. The cost estimates (by J. Stekly) for the magnet components alone are summarized below: (costs in millions of dollars):

	20 kG: (conventional)	40 kG:	60 kG:
Bending magnets	8.	29	41.
Quadrupoles	2.5	9.	12.
Total	10.5	38.	53.

These high-field magnet cost estimates are considerably higher than for the conventional iron-copper magnets, by amounts greater than any potential savings in power equipment or reduction of orbit size.

M. A. Green also presented some estimates on storage ring costs in his papers at the Brookhaven study[4, 5], for 100-GeV and 1000-GeV. Magnet costs are higher than for synchrotron magnets of the same energy, due to the use of two intersecting rings. Costs of power supplies and of refrigerators are much smaller for storage rings operating in the dc mode. A general conclusion is that no major cost savings relative to conventional magnets are apparent.

Conclusions:

Clearly, superconducting magnets are going to be developed with increasing speed in the years ahead, and will be applied to many laboratory needs. The technology is ripe for exploitation in a wide variety of magnets for special purposes. Costs may not always be lower than conventional magnets but will be justified by the importance of developing and expanding the new technology and by the special features available, such as high fields and small dimensions.

The chief area in which superconducting magnets have not been adequately tested is the use in systems employing a large number of units. When properly developed, the use of large systems must eventually be proven practical and may possibly be of lower cost than for conventional systems. The need at present is the rapid development of systems experience. For example, a system of superconducting magnets and quadrupoles should be planned for the earliest possible inclusion in at least one of the NAL emergent beam runs and target stations. This may well be one of the first major superconducting systems to be developed and used.

However, with the present lack of experience in systems planning and the consequent uncertainties in the uniformity and reproducibility of units in a system, it seems unwise to stop the present development and construction of the conventional magnet system for the NAL 200-GeV machine. The time required for adequate development of the special superconducting magnets, and to gain experience in the use of these units in systems, would certainly postpone the completion date of the 200-GeV machine as a working accelerator by several years. Such delay is high undesirable in view of the urgent scientific need for completion of this accelerator facility.

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